SCIENCE WITH THE SQUARE KILOMETRE ARRAY

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Abstract

The Square Kilometre Array (SKA) is the centimeter- and meter-wavelength telescope for the 21$^{\rm st}$ Century. Its Key Science Projects are (a) The end of the Dark Ages, involving searches for an H I signature and the first metal-rich systems; (b) Testing theories of gravitation using an array of pulsars to search for gravitational waves and relativistic binaries to probe the strong-field regime; (c) Observations of H I to a redshift $z \approx 2$ from which to study the evolution of galaxies and dark energy. (d) Astrobiology including planetary formation within protoplanetary disks; and (c) The origin and evolution of cosmic magnetism, both within the Galaxy and in intergalactic space. The SKA will operate over the wavelength range of at least 1.2 cm to 4 m (70 MHz to 25 GHz), providing milliarcsecond resolution at the shortest wavelengths.

1 Introduction

In the latter half of the 20$^{\rm th}$ Century, we discovered unimagined sources and phenomena. Observations at radio wavelengths laid the foundation for many discoveries, including non-thermal emission mechanism, active galaxies, the cosmic microwave background (CMB), pulsars, gravitational lensing, and extrasolar planets. In the 21$^{\rm st}$ Century, we seek to understand the Universe that we inhabit.

Under development by an international consortium, the Square Kilometre Array (SKA) is a centimeter- and meter-wavelength telescope envisioned as being one of a suite of multi-wavelength facilities for the 21$^{\rm st}$ Century. Its original motivation was as a "hydrogen array," a telescope sensitive enough to detect the 21-cm H I line from a Milky Way-like galaxy at a redshift of order unity. Since then, the international community has developed a set of Key Science Programs that are intended to address a much broader range of fundamental questions in astronomy, physics, and astrobiology [1,2]. In the spirit of the European Astronet Roadmap and the U.S. *New Worlds, New Horizons* Decadal Survey, we shall discuss the key science in two broad categories, "origins" and "fundamental physics," recognizing that the divisions between these two categories is, at times, indistinct.

2 Key Science: Origins

One of the motivations for observing the Universe is that it can answer fundamental questions about how we originated, questions that have been posed since the beginning of humanity.

2.1 The Dark Ages, Cosmic Dawn, and the Epoch of Reionization

At a redshift around 1100, the Universe became largely neutral as protons and electrons combined to form the first hydrogen atoms, while today the Universe is largely ionized. Observations of the highest redshift quasars and analysis of the Wilkinson Microwave Anisotropy Probe (WMAP) observations indicate that stars were forming, and Reionization was underway, by redshifts $z \approx 6$–15. These redshifts are so large that only observations at wavelengths longer than 1 μm are useful, and the SKA will play a key role in probing these epochs.

As the first stars and accreting black holes begin to illuminate their surroundings, they should ionize and heat the surrounding H I in the intergalactic medium (IGM). Its excitation (spin temperature) will decouple from the temperature of the CMB, and a complex, time-dependent patchwork of (highly redshifted) H I emission or absorption against the CMB is predicted. At $z \lesssim 10$, the (redshifted) H I line should appear in emission as the gas is being heated to the point of starting to reionize, while at higher redshifts, the signal should switch into absorption, as the gas remains colder than the CMB. The goal of the SKA is to detect this highly-redshifted H I emission and absorption, which in turn will constrain the formation of the first structures.

Further, carbon monoxide (CO) has been detected in some of the most distant radio-loud quasars. The presence of "metals" at $z \approx 6$ is problematic, as the time scale for these elements to be produced in the first stars and then distributed is uncomfortably close to the age of the Universe at that time. The shorter-wavelength capabilities ($\sim$ 1.5 cm) of the SKA will be used to conduct even more sensitive searches for CO emission from distant, radio-loud objects and constrain the time scales on which the first stars would have had to form, fuse these elements, then disperse them back to the surrounding medium.

2.2 Galaxy Formation and Evolution

The original focus of the SKA was observations of the 21-cm H I line from galaxies, and such observations remain a significant focus of the SKA Science Case. Neutral hydrogen is the raw material from which stars form. The peak of the star formation rate in the Universe occurred at $z \sim 1$–2. The SKA will be able to probe the evolution of H I to this crucial point in the assembly of galaxies.

Although the star formation rate in the Universe peaks at $z \sim 1$–2, the density of H I appears to be relatively constant until relatively recently. Moreover, most galaxies contain insufficient amounts of gas to power their star formation for a Hubble time. These observations suggest that galaxies are able to tap a reservoir(s) of gas in order to power their star formation. This reservoir might be the IGM, from hot gas condensing onto galaxies or delivered through "cold accretion" streams, or it might be in the form of mergers or both. The very deepest observations often show extended H I halos around galaxies or low column density clouds in their neighborhoods, and it is well known that the H I gas is often an indicator of potential merger activity in groups of galaxies. However, the current generation of observations is not sufficiently deep to provide definitive answers to the question of the balance between accretion and mergers in the galactic gas budget.

2.3 Astrobiology: The Cradle of Life

The current picture of planetary assembly, supported by considerable evidence from our solar system and young stars in star formation regions, is that it begins in a disk composed of dust and gas. The initial dust grain size is probably sub-micron, comparable to that for interstellar dust particles. Within the proto-planetary disk, the dust grains begin to "stick" together. As they do so, they decouple from the gas and begin to interact gravitationally. The dust grains accrete, first forming "pebbles," then "boulders," and finally planetesimals. Probing the disk when pebbles are forming and accumulating into boulders requires observations at wavelengths comparable to the size of the particles ($\sim$ 1 cm). With its high frequency capabilities, the SKA will be positioned uniquely to probe the assembly of planets. Moreover, it is planned for the SKA to be able to obtain milliarcsecond resolution. At the distance of nearby star forming regions ($\approx$ 150 pc), 1 AU subtends an angle of approximately 7 mas. Thus, the SKA will be able to resolve the inner portions of proto-planetary disks. For a solar-mass star, the orbital period at a distance of 1 AU is 1 yr, so the SKA may even make "movies" of planet formation.

In addition, a number of large ($>$ 10 atom) prebiotic molecules are being discovered in interstellar space. Typical transition frequencies for these molecules are 1–20 GHz, with larger molecules having transitions at lower frequencies. The SKA will search for these prebiotic molecules and explore the extent of organic chemistry and the precursors of life in interstellar space.

3 Key Science: Fundamental Physics

A second motivation for astronomy is that it can motivate or provide tests of theories of fundamental physics. For instance, observations of gravitational lensing by the Sun provided key early support for Einstein's General Theory of Relativity (GR), which now finds widespread use, such as in the Global Positioning System (GPS).

3.1 Strong Field Tests of Gravity using Pulsars and Black Holes

Observations of the pulsar PSR B1913+16 have already provided an indirect detection of the gravitational radiation predicted in GR (and the 1993 Nobel Prize in Physics). The Galaxy should contain systems capable of providing even more stringent tests, and the sensitivity of the SKA will be such that it will detect a significant fraction of the 20,000 rotation-powered radio pulsars within the Galaxy that are beamed in our direction.

Models of the Galactic pulsar population predict that there should be at least one pulsar-black hole binary in the Galaxy. As a black hole is the most compact object that should exist, the regular pulsations from a pulsar ("clock") in its environment would provide stringent tests of GR. At a basic level, the pulsar timing will reveal the properties of the black hole companion, such as its mass and angular momentum, in a manner similar to how timing observations have measured the mass of both components in double neutron star systems. Higher order tests of GR can also be conducted, such as of the "no-hair" theorem that predicts that a black hole is described entirely by its mass, angular momentum, and electric charge, and which also predicts a simple relation between its angular momentum and quadrupole moment. Further, the supermassive black hole in the Galactic center should contain a number of pulsars in orbit about it, pulsars that have escaped detection because current instruments do not have sufficient sensitivity at the frequencies ($>$ 10 GHz) required to mitigate the severe interstellar scattering effects along the line of sight.

The SKA is expected to discover millisecond pulsars across the sky. With their exquisite timing stability, this network of millisecond pulsars (pulsar timing array) can serve as a many-armed gravitational wave detector, searching for timing distortions due to the passage of very low frequency gravitational waves ($\sim$ nHz). Generally, cosmic sources are expected to produce a spectrum of gravitational waves, and the SKA pulsar timing array will probe a regime in which gravitational waves may be produced by binary supermassive black holes resulting from galactic mergers, cosmic strings, or during the initial inflationary epoch of the Universe.

3.2 The Origin and Evolution of Cosmic Magnetism

Electromagnetism is one of the most accurate physical theories, and it is clear that magnetic fields fill intracluster and interstellar space, affect the evolution of galaxies, contribute significantly to the total pressure of interstellar gas, are essential for the onset of star formation, and control the density and distribution of cosmic rays in the interstellar medium. Nonetheless, fairly basic questions remain about the origin and evolution of cosmic magnetic fields. A radio wave propagating through a magnetized plasma undergoes Faraday rotation, providing the SKA with a unique probe on cosmic magnetic fields. The SKA will be able to form a grid of Faraday rotation measures, with a typical separation of about $90''$ between lines of sight.

With this grid, a detailed picture of the Galactic magnetic field will be produced, and similar measurements will be used to probe the fields in nearby galaxies. Such a detailed model for galactic magnetic fields in turn can discriminate between various origins for magnetic fields in galaxies, whether the fields are in some sense primordial or were generated at later times by a dynamo action (e.g., α-Ω dynamo).

For nearby clusters of galaxies, the rotation measure grid will be sufficiently dense to probe the field within the clusters themselves, in contrast to the current situation in which only properties averaged over many clusters can be determined. A detailed view of the magnetic field structure within clusters will in turn allow probes of the interaction between magnetic fields and the hot, X-ray emitting gas as well as the interplay between "heating" mechanisms for a cluster (e.g., mergers, radio jets from active galactic nuclei near the center of clusters) and the cooling provided by the X-ray emission.

Finally, with the deepest SKA observations, magnetic field measurements at high redshift ($z > 2$) will be possible. Complementing those in nearby galaxies, observations of distant galaxies may trace directly the enhancement of the magnetic field by a dynamo (or illustrate that a dynamo is not responsible for its origin).

3.3 Cosmology and Dark Energy

The H I emission from galaxies can be used to study the galaxies themselves, or it can be used to identify test masses from which one can conduct cosmological observations. If the SKA can observe the H I emission from galaxies out to a redshift of order unity over much of the sky ($\sim 2\pi$ sr), it will survey a significant volume of the Universe (~ 100 Gpc^3). Within this volume should be more than one billion galaxies, from which the galaxy power spectrum as a function of redshift can be determined. At the time of recombination, acoustic oscillations in the intergalactic plasma should have been "frozen in." These baryon acoustic oscillations are detected today in the galaxy power spectrum, and they serve as a standard ruler. Importantly, the SKA's sensitivity should be such that they can be determined as a function of redshift. The SKA experiment will determine the change in the apparent angular size of these acoustic oscillations as a function of redshift. When combined with measurements of the size of these oscillations seen in the CMB, one can obtain a measure of the cosmic evolution of the Universe. In particular, the influence of dark energy from the time of the formation of the CMB to $z \sim 1$ can be probed, thereby constraining the equation of state of the Universe. Crucially, the accuracy of measurements of this sort depends upon the total number of objects detected. The large sample size of the SKA surveys will provide unparalleled precision.

An alternate approach to dark energy studies with H I is intensity mapping. The relevant scale for BAOs is about 150 Mpc, much larger than the size of an individual galaxy, or even a group of galaxies. Thus, rather than attempting to resolve individual galaxies, intensity mapping seeks to detect the integrated emission from galaxies. Once the integrated emission is detected, however, the approach to BAO studies of dark energy is conceptually similar in that the objective is to detect BAOs via a power spectral analysis of the H I emission.

4 SKA Precursors, Pathfinders, and Phase 1

One of the original motivations for the SKA Key Science Programs was that they provide a qualitative improvement on existing radio wavelength observations. To reach this objective, however, will require a solid observational foundation or "science pathfinding" using existing and under-construction telescopes, and this science foundation is being laid with observations at telescopes around the world. The observational programs being conducted are diverse, but span the entire SKA Science Case. Further, it is likely that there will be a "positive feedback loop" between the SKA Science Case and the on-going programs. Just as the SKA Science Case has helped to influence some of the current observational programs being conducted, the results of these observational programs will influence the evolution of the SKA Science Case, as surveys push to deeper fields and larger sky expanses.

One of the key strengths of an interferometer is that it degrades gracefully as receptors are removed from operation. Conversely, an interferometer can begin science operations well before it has reached its full complement of receptors. Such is the notion of the SKA Phase 1: Rather than waiting for the construction of the full SKA to be completed, significant science results can be produced when the array has only a fraction of its full complement of receptors. A notional value for the scale of SKA Phase 1 is that it would be 10% of the capability of the SKA. Key scientific motivations for SKA Phase 1 are two aspects of the full SKA Science Case, namely, studies of H I over cosmic time, particularly observations of H I during the Epoch of Reionization, and fundamental physics as probed by pulsar observations, particularly detecting gravitational waves.

Between the on-going science programs at existing and near-future telescopes, and the science that they will motivate first in SKA Phase 1 and then in the SKA itself, radio wavelength observations are poised to continue their impressive record of helping us understand the Universe in which we live.

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References

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